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Towards instantaneous spectrally controlled interferometry

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ABSTRACT

Spectrally controlled interferometry (SCI) is a method which presents a host of advantages over traditional coherent and white light interferometry. As its name suggests, the source spectrum is precisely controlled to produce localized fringes whose location and phase are tunable. The approach has been demonstrated to produce accurate interferometric measurements of planar and spherical optics in the presence of detrimental back reflections over a large range of cavity sizes. Phase shifted measurements of single surfaces can be done without any means of mechanical phase shifting. Additionally, existing systems can be converted to be SCI compatible as the method is implemented entirely at the source level of the instrument.

Previous demonstrations of this method have applied temporal phase shifting, but use of the SCI method does not preclude the use of alternative measurement techniques. While traditionally, SCI measurements are acquired by shifting the phase of the spectrum modulation function, here we present an alternative method for phase shifting via mean wavelength shift. It is a convenient extension of SCI because typically source parameters are already controlled electronically and shifting mean wavelength of the source adds no additional complication or modification to the existing hardware. By utilizing wavelength shifting novel architectures for instantaneous measurements become possible.

In this paper we present two methods of instantaneous surface measurements: using carrier fringe approach and simultaneous PSI by mean wavelength shift. Various phase measurements of multiple surface cavities via both methods are presented to demonstrate the capability. Comparisons are made to traditional SCI and standard coherent phase shifting measurements. Limitations and sources of noise are addressed as well.

Keywords: spectrally controlled interferometry, white light interferometry, coherence, metrology, interferometry, instantaneous, wavelength shifting, carrier fringe

1. INTRODUCTION

Spectrally controlled interferometry is a convenient solution for optical surface metrology which combines the flexibility of laser interferometry with the fringe localization of white light interferometry. Via precise control over the spectral distribution of the source, localized fringes can be realized in an optical path difference (OPD) unbalanced interferometer, such as the Fizeau, and tuned to a large range of measurement distances without the use of a mechanically translating reference surface. Furthermore, these fringes can be manipulated to achieve phase shifting interferometry (PSI) measurements in previously inaccessible configurations. This method has been demonstrated to provide successful measurements of very thin planar cavities,[1] multiple surface cavities on standard optical components,[2] spherical cavities,[3] and simplified measurements of refractive index homogeneity.[4]

Previous demonstrations of SCI have employed a temporal phase shifting method by way of spectral modulation function phase control. While this provides a convenient approach to phase shifting that is free of the mechanical nonlinearities and tedious calibration associated with piezoelectric transducers (PZTs),[5] there are applications in which an instantaneous method of phase measurement would be advantageous, for example, in environments dominated by mechanical vibrations[6] or transient phenomena.[7,8]

Several methods for instantaneous and vibration insensitive phase measurement have been explored which provide an adequate means to acquire high quality phase information in the presence of mechanical vibration and

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environmental fluctuations. These approaches are commonly implemented by sampling the measured wavefront with parallel channels to acquire more information in a shorter time scale. This prevents the need to acquire interferograms over time, when the environmental effects can have a more significant impact on the measurement. The parallel channels of sampling can either be done via amplitude splitting[9] or through means of polarization filtering.[10]

Here we present two alternative approaches for instantaneous phase shifting that are compatible with the SCI method. The first is the carrier fringe method.[11] Carrier fringe is a readily available approach that can easily be implemented in Fizeau interferometers. However, this method has its drawbacks and most predominantly, the measurement comes at the penalty of significant retrace errors if the interferometer is not well designed.

The second method uses change in the mean wavelength of the SCI source to achieve effective phase shifting and provides an alternative to the previously demonstrated temporal SCI phase shifting. Furthermore, there in an opportunity to produce an instantaneous SCI phase shifting architecture by utilizing a parallel sampling of a resulting interferogram with relative shifts in the mean wavelength to acquire a complete PSI measurement over shortened time scales.

2. THEORY

2.1 Spectrally Controlled Interferometry

Spectrally controlled interferometry employs the Wiener-Khinchin Theorem to produce a desirable coherence function and fringe distribution in measurement space through manipulation of the source spectral distribution in the optical frequency,ν, domain. A nominally broadband Gaussian source, $g(\nu;\nu_0)$, centered at the mean frequency, ν_0 with bandwidth, $\Delta\nu$, is combined with a sinusoidal modulation function,$m(\nu;f,\theta)$ whose control parameters: modulation frequency, f and phase, θ, have a direct relationship to producible fringe characteristics,[2] shown in Equation (1).

$$g_{SCI} = g(\nu;\nu_0) \times m(\nu;f,\theta) = e^{-\frac{\nu-\nu_0}{\Delta\nu}} \left[\frac{1}{2} + \frac{1}{2}cos(f\nu+\theta)\right] \tag{1}$$

The coherence function of the source is related to the spectral distribution via the Fourier transform, where the optical frequency is converted into the time delay variable, τ. The time delay between two interfering wavefronts, τ, can be converted into a measure of OPD by the following relationship, $OPD = \tau c$, where c is the speed of light.[12]

As a result of the Convolution Theorem, the final coherence function, γ_{SCI} from Equation (1) is a combination of the nominal coherence envelope at the zero OPD location with additional copies of the nominal coherence envelopes at locations proportional to the modulation frequency, f, with an additional phase term, proportional to the phase, θ, of the modulation function, shown in Equation (2).[2]

$$\gamma_{SCI} = e^{-\Delta\nu\tau} + \frac{1}{2}e^{-i\theta}e^{-\Delta\nu(\tau-f)} + \frac{1}{2}e^{i\theta}e^{-\Delta\nu(\tau+f)} \tag{2}$$

These side band coherence envelopes are both tunable in location and in phase via electronic control over the modulation function parameters. This benefit enables highly effective surface isolation without the need to meet the path length matching condition required of the nominal coherence envelope centered at zero OPD. The maximum contrast of fringes in the side band coherence envelopes is limited to the $\frac{1}{2}$ due to the normalization of the coherence function and the functional form of the modulation function.[2]

2.2 Carrier Fringe

Carrier fringe interferometry is a phase shifting method which combines a method specific alignment procedure and processing algorithm to acquire a complete phase measurement. Because all processing for phase calculation are completed from a single interferogram frame, the method is vibration insensitive (for short camera exposure times).[11]

In order to achieve this instantaneous measurement, the traditional cavity nulling procedure is forgone and instead, a large amount of tilt (commonly done with fringes oriented at a 45 degree angle) is induced into the measurement cavity and a single frame is acquired. The interferogram is processed in the Fourier domain to isolate the underlying surface shape and phase.[11] There is an underlying assumption of this method that the slope of the surface under test is continuous and slowly varying.

For traditional white light sources, the narrow width of the coherence function envelope can preclude successful fringe localization due to the large amount of tilt across the full aperture of the surface. With the SCI source, the bandwidth of the source, $\Delta\nu$, is also a controllable parameter, allowing coherence envelope with to be expanded or contracted as necessary based on the measurement geometry. This provides flexibility for the required alignment conditions for larger aperture optics. The carrier fringe method provides a readily available method to achieve instantaneous phase measurement for SCI.

Despite its convenience, this method has associated challenges which can limit the overall accuracy of the final measurement results. First, the correct amount of tilt must be aligned to properly sample the carrier fringe frequency. This condition is necessary to match the filtering operation done in the Fourier domain of the processing algorithms.[13] Furthermore, because the required fringe density is high, the Fizeau interferometer is no longer operating in a common path mode and is susceptible to significant retrace errors. Measurement quality for many commercial interferometers can be severely reduced even with small magnitudes of introduced tilt and these errors are often no longer be ignored.

2.3 Wavelength Shifting

An alternative to carrier fringe is phase shifting by mean wavelength change, presented here. Traditional phase shifting via wavelength shift for coherent interferometry is a well understood method based on its simple relationship between fringe phase, ϕ, OPD, and wavelength of light, λ,

$$\phi = \frac{2\pi OPD}{\lambda}. \tag{3}$$

The magnitude of the wavelength shift required to achieve a 2π phase shift is dependent on the OPD of the measurement cavity. There is a duality for this approach that often limits the practical implementation for these systems. For short cavities, a large dynamic range of wavelength shift is required to achieve the complete phase shift. Conversely, longer cavities require a much smaller dynamic range, but require a fine precision wavelength steps to achieve proper phase step intervals.

SCI offers a potentially convenient mechanism for wavelength based phase shifting as means for wavelength control are built into the method and can be controlled with a low amount of difficulty. However, this approach requires careful evaluation of the spectral characteristics of the light source and the relationship between the formation of fringes and phase shift due to wavelength shift of the source. For this approach, it is more convenient to express the mathematical relationships and behavior in terms of the optical frequency, ν.

First, recall that the complete SCI source spectrum is composed of two independent signals, a nominal Gaussian bandwidth source and a modulation function. The latter will be assumed to be stationary at a given frequency and phase, while the former will be shifted by a nominal amount, $\Delta\nu_0$. This is shown graphically, in Fig. 1 where the solid line represents the initial spectral distribution and the dashed line represents the resulting spectral distribution whose mean frequency has been shifted by, $\Delta\nu_0$.

$$\gamma_{WSCI} = e^{-2\pi i\Delta\nu_0\tau}e^{-\Delta\nu\tau} + \frac{1}{2}e^{-2\pi i\Delta\nu_0(\tau-f)}e^{-i\theta}e^{-\Delta\nu(\tau-f)} + \frac{1}{2}e^{-2\pi i\Delta\nu_0(\tau+f)}e^{i\theta}e^{-\Delta\nu(\tau+f)} \tag{4}$$

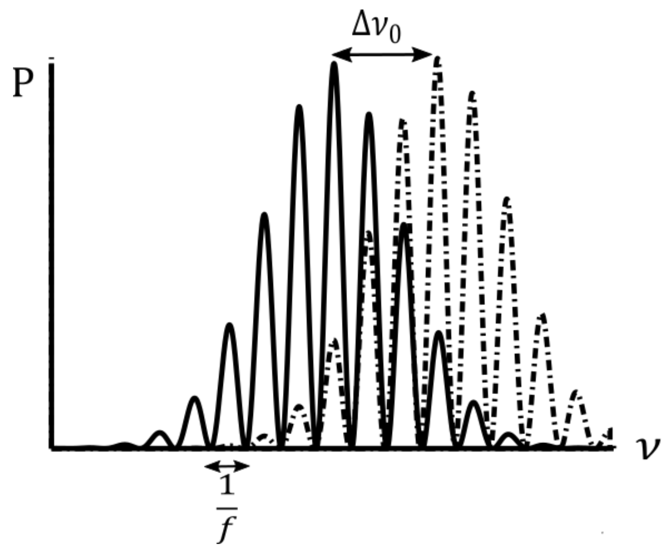

Figure 1. Mean frequency shift of the SCI source spectrum. P is the power spectral density, ν is the optical frequency, f, is the modulation function frequency, and $\Delta\nu_0$ is the shift in mean frequency.

This shift in the mean frequency results in a linear complex phase term, $e^{(-2\pi i\Delta\nu_0\tau)}$, with the same argument from Equation (3) in the coherence function as a result of the Fourier transform relationship. However, due to the convolution operation, there is a change of variables in the phase term for the additional side band coherence envelopes, $e^{(-2\pi i\Delta\nu_0(\tau\pm f))}$.

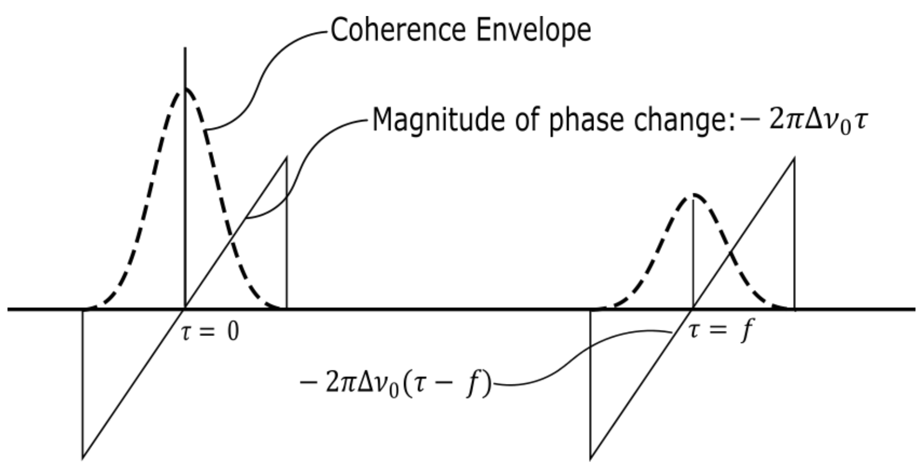

Figure 2. Graphical representation of the relationship between coherence envelope location and phase shift due to mean optical frequency shift. The dashed lines represent the locations of the nominal coherence envelope (left) and the SCI side lobe (right). The solid linear functions (equations provided) represent the magnitude of the phase change, with a null value located at the centers of the envelopes.

As a result, the center of the nominal coherence envelope *and* the center of the side band envelopes are intrinsically insensitive to mean frequency shift and thus offer no effective phase shift if the measurement cavity is tuned to either of these locations. The final coherence function, γ_{WSCI} is shown completely in Equation (4) and this effect is shown graphically in Fig. 2.

From a physical interpretation, this phenomenon can be explained via the stationarity of the modulation function. The modulation frequency provides the unique selection of optical frequencies that will appropriately constructively interfere at a single, fixed point in space. Regardless of the selected bandwidth for analysis, the location of the constructive interference and the relative phase relationship between adjacent selected optical frequencies is fixed, similar to that of a resonant optical cavity. The phase of the produced interference fringes is inherently defined by the phase of the modulation function, which is by previous definition, stationary.

This realization offers an interesting advantage for measurement implementation for wavelength shifting SCI. While the modulation frequency and cavity length must be slightly detuned to achieve an effective phase shift from mean wavelength shift, the same behavior is observed regardless of SCI fringe location. With the same prescribed magnitude of cavity detuning, the required wavelength shift for 2π phase shift is constant, providing a fixed phase relationship for localized fringes across all measurement space. As a result, the equation in Eq (3), can be rewritten with cavity detuning parameter, ϵ, and is independent of OPD.

$$\phi = \frac{2\pi\epsilon}{\lambda}. \tag{5}$$

Extension of this principle to practical instantaneous measurement schema becomes feasible without the constraint of retuning based on measurement cavity length. One potential method is an SCI interferometer with a multiple camera architecture which utilizes wavelength-tuned bandpass filters in each detector path to produce relative phase shifted interferogram frames simultaneously. This method can be accomplished with as little as three cameras for use with any standard three frame phase unwrapping algorithms.

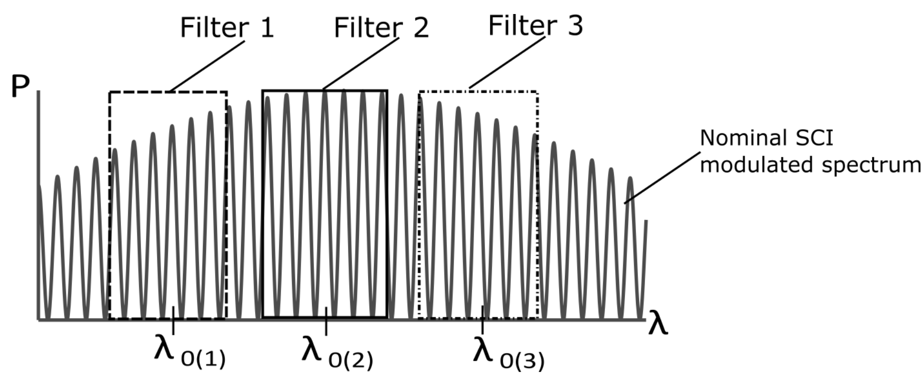

Figure 3. Nominal SCI spectral modulation (P represents power spectral density) with three mean wavelength, $\lambda_{0(1)}, \lambda_{0(2)}, \lambda_{0(3)}$ shifted bandpass filters which provide relative phase shifts proportional to cavity detuning, ϵ.

Due to the Fourier relationship of spectral distribution and the coherence function, the system is linear and spectral manipulation can occur at any point before signal integration at the detector. For example, a nominal SCI source can be coupled to a Fizeau interferometer system and the relative wavelength shifts can be induced at each adjacent camera after the light has traversed the optical cavity. Each filter in adjacent detection channels may have a prescribed bandpass filter, shown in Fig. 3, with an appropriately shifted mean wavelength, $\lambda_{0(1)}, \lambda_{0(2)}, \lambda_{0(3)}$, respectively, for a unique value of cavity detuning,ϵ, per Eq.(5).

3. EXPERIMENTAL RESULTS

3.1 Carrier Fringe

In order to demonstrate the carrier fringe measurement modality implemented in tandem with the SCI method, an Äpre Instruments S100|HR Fizeau interferometer upgraded with SCI functionality is used to measure the front surface of an 80 mm diameter, 12 mm thick plane parallel plate with a $\frac{\lambda}{20}$ transmission flat. Two measurements are taken: the first with the standard method of phase shifting SCI via phase shifting of the modulation function and the second with the carrier fringe phase measurement technique.

In both measurement scenarios, secondary back reflections from the three surface cavity would preclude measurement with a traditional coherent laser source. The SCI source enables front surface isolation with the coherence envelope width controlled to 250 microns, for both measurement modalities.

The measured and processed phase map results were processed with Äpre Instruments REVEAL$^{\text{TM}}$metrology software and are shown in Fig.4 for the standard phase shifting SCI method (a) and the carrier fringe SCI

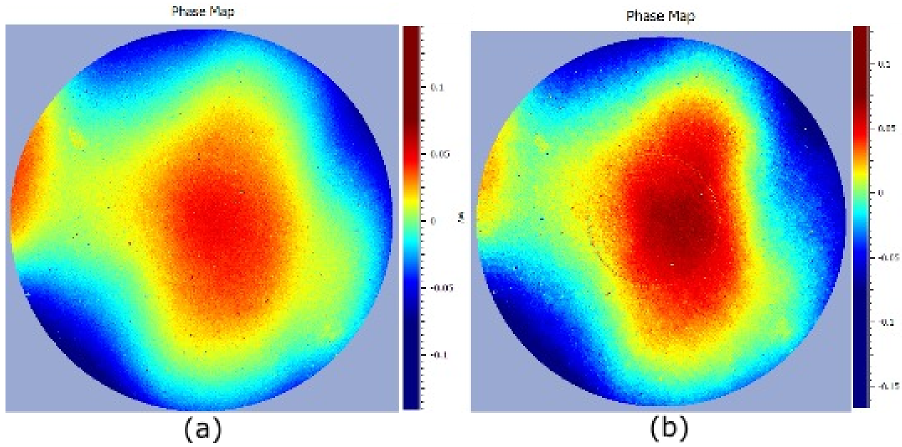

Figure 4. Calculated phase maps from standard phase shifting SCI method (a) and carrier fringe SCI method (b). Phase map color scaling $\in [-0.075, 0.075]$ waves. Zernike Tilt removed in both phase maps.

measurement modality (b) with colormap scaling $\in [-0.075, 0.075]$ waves and Zernike Tilt removed. For the phase shifting SCI phase map, the reported Peak to Valley (PV) value is 0.287 waves, with a Root Mean Square (RMS) value of 0.027 waves and a PVr value of 0.156. For the carrier fringe SCI phase map, the reported PV value is 0.296 waves, with an RMS value of 0.034 waves and a PVr value of 0.193. The difference in reported PVr for the measurement is $< \frac{\lambda}{20}$ and demonstrates a high degree of correlation. Small differences in the final phase maps are due to differences in phase unwrapping algorithms and processing noise inherent in the carrier fringe method.[13]

3.2 Wavelength Shifting SCI

While the proposed measurement architecture for instantaneous wavelength shifting SCI described in Sec. 2.3 is feasible to implement, it requires procuring optical filters with precise requirements and tight tolerances for achieving appropriate wavelength response curves. The same functionality can be realized with a specifically designed SCI source and the built in trigger functionality for most off the shelf cameras.

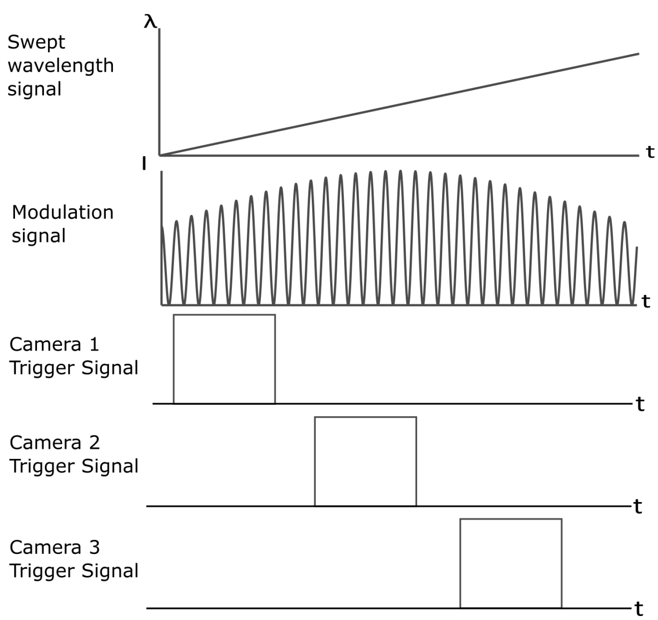

Figure 5. Conceptual signal diagram for swept SCI source with 3 delayed camera trigger signals to achieve mean wavelength shift for producing three phase shifted interferograms.

A swept SCI source was designed to produce a modulated, time dependent wavelength based source signal. Next, three identical cameras are synchronized to the SCI source sweep cycle. The effective mean wavelength of the integrated signal at each camera can be shifted by utilizing the internal trigger delay functionality. A concept diagram of the source signal and detection scheme is shown in Fig. 5. This measurement scheme is highly flexible, allowing for different magnitudes of wavelength shift per varying detuning, ϵ, values. Furthermore, total acquisition time is proportional to source sweep time and inversely proportional to ϵ.

With this SCI source and trigger delay based wavelength filtering, quasi-instantaneous phase shifting measurements can be achieved with a three camera Fizeau interferometer design, shown in Fig. 6. The system is a one inch aperture, non polarization based interferometer. The cameras are co-aligned and calibrated with a standard feature recognition algorithm and registered to common alignment via an affine transform in the measurement processing.

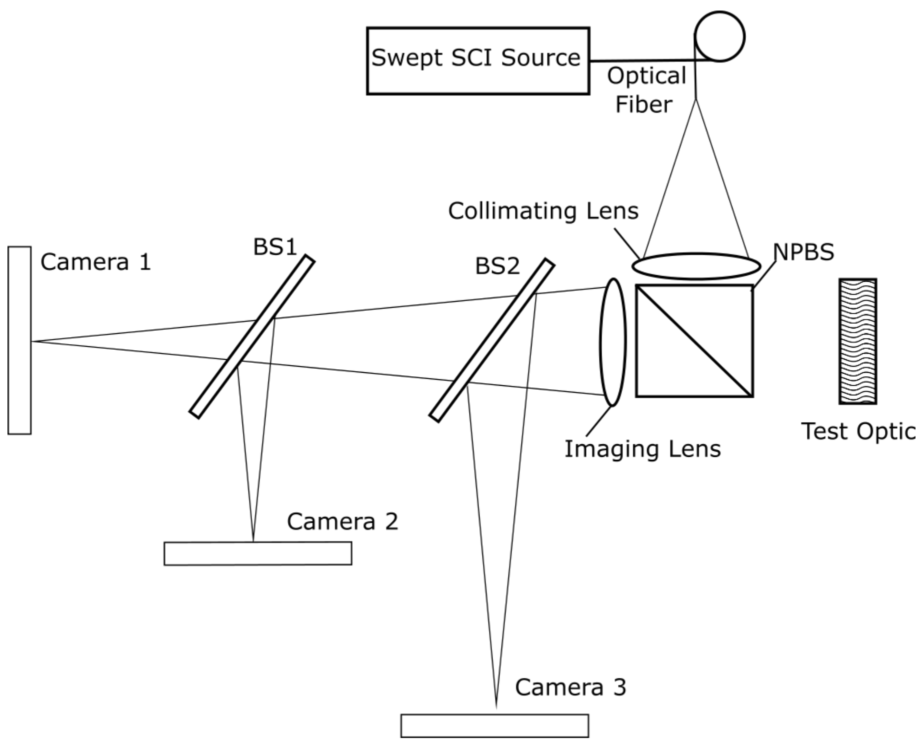

Figure 6. Experimental diagram for 3 camera non-polarization based Fizeau interferometer with scanning SCI source. No transmission flat is used in the experiment, and internal fringes of the plane parallel plate are produced and measured. BS : Beam splitter. NPBS: Non polarizing beam splitter cube.

A 10 mm plane parallel plate is used as a test optic for measurement. Internal fringes (interference between the front and back surfaces of the plane parallel plate), inaccessible to other modalities of interferometry, are analyzed without the use of a transmission flat. The coherence width of the SCI source is set to be approximately 300 microns with cavity detuning set to 100 microns. From Eq. (5), the required wavelength shift required for $\frac{\pi}{2}$ is 0.5 nm and this is accomplished with a relative trigger delay of 1 millisecond per each camera. With exposure times on the order of 3 milliseconds, the complete three frame stack is captured in 5 miliseconds. The interferograms are processed with a standard 3 frame, $\frac{\pi}{2}$ phase shift algorithm.

The measured and processed phase map results were processed with Äpre Instruments REVEAL$^{\mathrm{TM}}$metrology software and are shown in Fig.7 for the single measurement channel standard phase shifting SCI method (a) and the three camera wavelength shifting SCI measurement modality (b) with colormap scaling $\in [-0.15, 0.15]$ waves and Zernike Tilt removed. For the standard phase shifting SCI phase map, the reported PV value is 0.415 waves, with an RMS value of 0.079 waves and a PVr value of 0.360. For the three camera wavelength shifting SCI phase map, the reported PV value is 0.466 waves, with an RMS value of 0.079 waves and a PVr value of

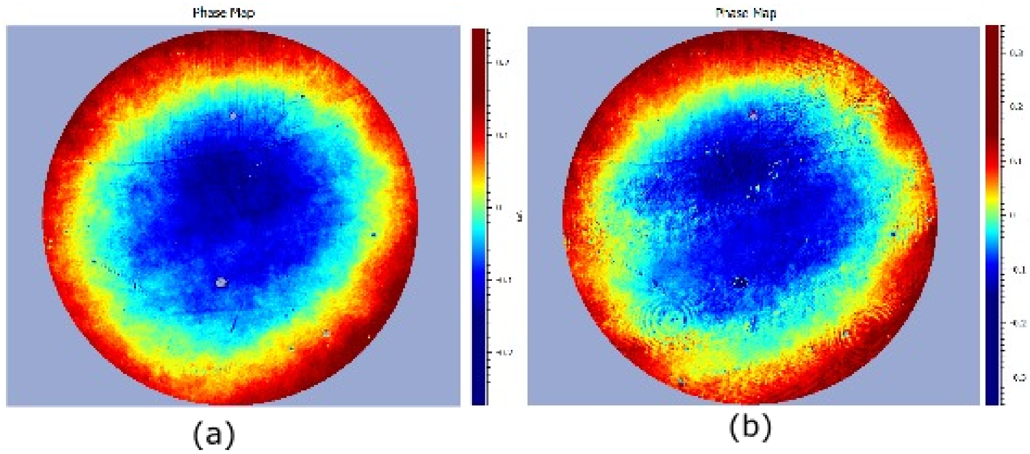

Figure 7. Calculated phase maps from standard phase shifting SCI method (a) and three camera based wavelength shifting SCI method (b). Phase map color scaling $\in [-0.15, 0.15]$ waves. Zernike Tilt removed in both phase maps.

0.366.

The difference in reported PVr for the measurement is $< \frac{\lambda}{100}$ and demonstrates a high degree of correlation. The wavelength shifting SCI phase map suffers from common sources of noise which plague multiple camera measurement schema including: pixel to pixel calibration errors, channel to channel intensity fluctuations, and non-common path spatial coherent effects. These errors manifest themselves in residual phase ripple and larger magnitudes of high frequency noise. These variations can be further explored and mitigated to reduce the residual errors and lower the noise floor of the wavelength shifting SCI measurements.

4. DISCUSSION

SCI provides a flexible measurement modality through non-mechanical control of fringe location and complete PSI measurements are possible through control of the modulation function phase. However, the SCI method is not limited to temporal phase shifting methods and its advantages can be leveraged in various measurement modalities for instantaneous phase measurement.

The carrier fringe method provides a readily available approach for instantaneous phase measurement that provides comparable results to complete PSI measurements with little modification to the experimental setup. The use of SCI in combination with this method allows more flexibility in fringe localization in the required large tilt alignment conditions with the added convenience of non-mechanical fringe location control.

Wavelength shifting SCI is a novel phase shifting approach which benefits from the inherent advantages of the SCI method while making efficient use of the available bandwidth of the source. While the method is fundamentally insensitive to mean wavelength shift for proper cavity tuning, phase shifting can be achieved and is proportional to the cavity detuning parameter, ϵ, regardless of measurement cavity length. While there is a penalty in the fringe contrast from this detuning, the contrast is far above the detection threshold for the majority of existing phase shifting algorithms. Additionally, the availability of 12-bit detectors help to mitigate the drop in contrast.

Wavelength shifting SCI provides an opportunity for instantaneous phase shifting to reduce effects from mechanical vibrations and transient effects through various presented architectures. While the wavelength shifted filter, mulitple camera measurement scheme provides a robust and fixed solution, an equivalent method can be accomplished with a swept SCI source and off the shelf cameras with trigger delay functionality. For this framework, the total acquisition time, and thus insensitivity to vibrations and environmental fluctuations, is proportional to the sweep cycle frequency of the SCI source and magnitude of the detuning.

Measurement results for both SCI carrier fringe and wavelength shifting SCI have been demonstrated and compared to standard phase shifting SCI measurement techniques with a high level of success. Instantaneous phase shifting methods can be a desirable measurement modality in environments dominated by vibration or large thermal and air turbulence and these methods can be used in tandem with the nominal SCI approach to leverage the advantages of both methods.

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